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A Deterministic Quantum Hash Framework for Multi-Scale Physical and Informational Systems

Abstract

A deterministic framework is introduced for constructing a quantum hash as a hybrid physical-informational descriptor applicable across multiple scales, from macroscopic physical systems to biological structures.[file:202] The formulation evaluates physically meaningful observables through an effective operator acting on a system state, combines these observables with entropy, energy scale, temporal indexing, and causal consistency constraints, and maps the resulting descriptor into a reproducible cryptographic representation.[file:202] The model preserves classical mass-energy scaling while incorporating an informational layer that enables deterministic fingerprinting of system configurations.[file:202] A continuous complex-valued representation and a discrete cryptographic representation are both defined so that the framework can serve as a reproducible identifier, provenance layer, and multi-scale indexing mechanism across computational, physical, and biological domains.[file:202]

The construction is not presented as a new fundamental observable of nature, but as a derived informational descriptor built on top of standard observables and normalized structural descriptors.[file:202] In this formulation, mathematical consistency requires explicit domain restrictions for the density operator, entropy normalization, scale parameters, and deterministic serialization of inputs prior to hashing.[file:202]

1. Introduction

The increasing integration of physical modeling, large-scale simulations, and data-driven workflows requires robust mechanisms for state identification, reproducibility, and traceability.[file:202] Physics provides well-defined observables, but it does not by itself provide a standard deterministic identifier that simultaneously scales across domains, preserves physical interpretability, and supports reproducible computational indexing.[file:202]

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A deterministic quantum hash framework is therefore defined as a structured mapping from physical parameters and system descriptors into an informational representation that remains interpretable, serializable, and cryptographically reproducible.[file:202] The approach is inspired by quantum statistical descriptions of systems, entropy-based information measures, and multi-scale physical modeling, while treating cryptographic hashing as a final representation layer rather than as a physical law.[file:202]

2. Theoretical Framework

2.1 Definition of the Quantum Hash

The quantum hash is defined as a deterministic informational descriptor associated with a system O at time t :

$$H_q(O; t) := \mathcal{H}(X_O(t), S(\rho_O(t)), E_O, T(t), \mathcal{C}(t), \mathcal{M}_O)$$

where the scalar observable summary $X_O(t)$ is given by

$$X_O(t) := \text{Tr}(\rho_O(t) \hat{H}_{\text{eff}}(t)).$$

Here, $\rho_O(t)$ is a density operator on a finite-dimensional or trace-class Hilbert space satisfying

$$\rho_O(t) \geq 0, \rho_O(t) = \rho_O(t)^\dagger, \text{Tr}(\rho_O(t)) = 1,$$

and $\hat{H}_{\text{eff}}(t)$ is a self-adjoint effective operator defined on a domain for which the trace expectation exists.[file:202] The term $\mathcal{M}_O$ denotes deterministic structured metadata required for reproducible identification of the system state, such as scale class, protocol, model version, or measurement context.[file:202]

This formulation makes explicit that the hash does not act directly on raw physical reality, but on a canonical tuple of mathematically and operationally defined descriptors.[file:202]

2.2 Definitions and Domains

The principal symbols are defined as follows:[file:202]

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- O : physical or informational system under consideration.
- t : physical or observational time associated with the state.
- $\rho_O(t)$: density operator of system O at time t , positive semidefinite, Hermitian, trace one.
- $\hat{H}_{\text{eff}}(t)$: self-adjoint effective operator encoding dynamical, structural, and informational contributions.
- $X_O(t) = \text{Tr}(\rho_O(t)\hat{H}_{\text{eff}}(t))$: expectation value of the effective operator.
- $S(\rho_O(t))$: von Neumann entropy.
- E_O : nonnegative energy-scale parameter associated with the system.
- $T(t)$: deterministic temporal index.
- $\mathcal{C}(t)$: causal consistency descriptor.
- $\mathcal{H}$: deterministic cryptographic mapping from a canonical serialized input to a hash output.[file:202]

For full mathematical consistency, the entropy and logarithmic energy terms require explicit domain restrictions. The entropy expression is well defined for density operators via spectral decomposition, with the convention $0 \log 0 = 0$, and the logarithmic term requires strictly positive energy, $E_O > 0$. [file:202]

2.3 Entropy Term

The entropy is defined as

$$S(\rho_O) := -\text{Tr}(\rho_O \log \rho_O),$$

which is nonnegative for density operators and vanishes for pure states.[file:202] To support bounded normalization across classes of systems, the normalized entropy is defined as

$$S_{\text{norm}}(\rho_O) := \frac{S(\rho_O)}{S_{\text{max}}}, S_{\text{max}} > 0,$$

where S_{max} is a reference maximum entropy for the class of systems under consideration.[file:202] To guarantee $S_{\text{norm}} \in [0,1]$, the model assumes

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$$0 \leq S(\rho_O) \leq S_{\max}.$$

For finite-dimensional systems of dimension d , a natural choice is $S_{\max} = \log d$; for more general classes, $S_{\max}$ must be defined by a class-specific bounded reference convention.[file:202]

2.4 Energy Scaling

The macroscopic energy scale is defined by

$$E_O = M_O c^2,$$

with $M_O \geq 0$ and c the speed of light in vacuum.[file:202] Because the continuous representation uses $\log_{10}(E_O)$, a strictly positive value is required, so the operational domain is

$$M_O > 0 \Rightarrow E_O > 0.$$

This condition excludes the degenerate zero-mass case from the logarithmic representation unless a separate regularization convention is introduced.[file:202]

2.5 Temporal Index and Causal Consistency

The deterministic temporal index is defined as

$$T(t) = T_0 + n \Delta t, n \in \mathbb{Z}, \Delta t > 0.$$

This provides a reproducible discrete label for sequential system states.[file:202] The causal descriptor is represented abstractly as

$$\mathcal{C}(t) := A(|t_A - t_B| - \Delta t),$$

where A is not treated as an arbitrary operator but as a deterministic decision or penalty functional whose codomain must be fixed by implementation.[file:202] For reproducibility, $\mathcal{C}$ should be encoded either as a binary admissibility flag, a bounded penalty in $[0,1]$, or a finite discrete code set, so that it can be serialized deterministically prior to hashing.[file:202]

2.6 Effective Operator Decomposition

The effective operator is decomposed as

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$$\hat{H}_{\text{eff}} = \hat{H}_0 + \hat{H}_F + \hat{H}_S + \hat{H}_{\text{corr}} + \hat{H}_{\text{ent}},$$

where $\hat{H}_0$ collects baseline contributions, $\hat{H}_F$ encodes field contributions, $\hat{H}_S$ captures entropy-related terms, $\hat{H}_{\text{corr}}$ accounts for scale corrections, and $\hat{H}_{\text{ent}}$ represents entanglement-like or correlation-sensitive contributions.[file:202] To preserve the reality of $X_O(t)$, each term is assumed self-adjoint or the total sum must be self-adjoint.[file:202] To avoid redundant scale double counting, logarithmic corrections already encoded in the continuous representation should not be reintroduced independently inside $\hat{H}_{\text{corr}}$ without an explicit cancellation or calibration rule.[file:202]

3. Continuous Representation

3.1 Entropy Correction Term

An entropy-dependent correction term is defined as

$$\text{Correction}(O; t) := \kappa (S_{\text{norm}}(\rho_O(t)) - S_{\text{ref}}),$$

where κ is a global scale parameter and $S_{\text{ref}} \in [0,1]$ is a reference normalized-entropy level.[file:202] Since $S_{\text{norm}} \in [0,1]$, the correction term lies in the bounded interval

$$\text{Correction}(O; t) \in [-\kappa S_{\text{ref}}, \kappa(1 - S_{\text{ref}})].$$

This makes explicit that the correction is bounded whenever κ is finite.[file:202]

3.2 Complex Continuous Descriptor

The continuous complex representation is defined by

$$\text{Re}(H_q^{\text{cont}}(O; t)) = \log_{10}(E_O) + \frac{\kappa}{100} (S_{\text{norm}}(\rho_O(t)) - S_{\text{ref}}),$$

$$\text{Im}(H_q^{\text{cont}}(O; t)) = \gamma S_{\text{norm}}(\rho_O(t)), \gamma \geq 0,$$

and therefore

$$H_q^{\text{cont}}(O; t) = \text{Re}(H_q^{\text{cont}}(O; t)) + i \text{Im}(H_q^{\text{cont}}(O; t)).$$

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Under the constraints $E_O > 0$, $S_{\text{norm}} \in [0,1]$, and finite κ, γ , the continuous descriptor is always well defined.[file:202] In addition, the imaginary part is automatically bounded:

$$0 \leq \text{Im}(H_q^{\text{cont}}) \leq \gamma.$$

The real part is not bounded in an absolute universal sense because it inherits the unbounded growth of $\log_{10}(E_O)$, but for any fixed system class with bounded energy interval $[E_{\min}, E_{\max}]$ it satisfies

$$\log_{10}(E_{\min}) - \frac{\kappa}{100} S_{\text{ref}} \leq \text{Re}(H_q^{\text{cont}}) \leq \log_{10}(E_{\max}) + \frac{\kappa}{100} (1 - S_{\text{ref}}).$$

3.3 Interpretation of Limits and Extreme Cases

The framework admits clear limiting cases:[file:202]

- **Pure-state limit:** if $S(\rho_O) = 0$, then $S_{\text{norm}} = 0$, $\text{Im}(H_q^{\text{cont}}) = 0$, and the real-part correction becomes $-\kappa S_{\text{ref}}/100$.
- **Maximum-reference entropy limit:** if $S(\rho_O) = S_{\max}$, then $S_{\text{norm}} = 1$, $\text{Im}(H_q^{\text{cont}}) = \gamma$, and the real-part correction becomes $\kappa(1 - S_{\text{ref}})/100$.
- **Reference-entropy point:** if $S_{\text{norm}} = S_{\text{ref}}$, the correction vanishes and $\text{Re}(H_q^{\text{cont}}) = \log_{10}(E_O)$.
- **Mass-scaling dominance:** for sufficiently large energy differences, the logarithmic energy term dominates the entropy correction, preserving multi-scale separation.
- **Degenerate energy case:** if $E_O = 0$, the logarithmic continuous representation is undefined and the model must either exclude the case or introduce a regularized surrogate.[file:202]

These cases clarify the role of parameters and ensure that the continuous representation has stable interpretation across scales.[file:202]

4. Discrete Representation

The discrete representation is defined through a cryptographic hash function:

$$h_q(O; t) := \text{SHA3-256}(\text{Serialize}(\Xi_O(t))),$$

where

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$$\Xi_o(t) := (H_q^{\text{cont}}(O; t), T(t), \mathcal{C}(t), \mathcal{M}_o)$$

is the canonical tuple of continuous descriptor, temporal index, causal code, and metadata.[file:202]
 For determinism, $\text{Serialize}(\cdot)$ must be specified unambiguously through a canonical ordering, fixed numeric precision, fixed unit conventions, and a stable encoding format such as UTF-8 JSON with sorted keys.[file:202]

This requirement is mathematically essential for reproducibility because identical physical inputs must generate identical serialized strings before hashing.[file:202] Without canonical serialization, the hash stage would remain implementation-dependent even if the physical model were well defined.[file:202]

5. Numerical Reference Scaling

Reference values are presented for Earth, the Solar System, the Milky Way, and the Universe, with the real part driven primarily by $\log_{10}(E_o)$. [file:202] For Earth, using $M_{\oplus} = 5.972 \times 10^{24} \text{ kg}$ and $E_{\oplus} = M_{\oplus} c^2 \approx 5.37 \times 10^{41} \text{ J}$, one obtains $\log_{10}(E_{\oplus}) \approx 41.73$, consistent with the reported scale.[file:202]

In this regime, the entropy correction is explicitly a small refinement of order $\kappa/100$, so the reported values remain dominated by the macroscopic energy scale unless κ is chosen unrealistically large.[file:202] This gives the model numerical stability across extreme scale differences while preserving an informational perturbation layer.[file:202]

6. Algorithmic Scalability and Complexity

The framework is not intrinsically tied to SHA3-256 and can be implemented with different deterministic cryptographic primitives, including SHA-2, SHA-3, BLAKE2, BLAKE3, or post-quantum compatible hashing layers, without changing the higher-level model structure.[file:202] This modularity follows from the fact that the model separates the descriptor-construction stage from the final cryptographic representation stage.[file:202]

The computational complexity is dominated by state preparation, evaluation of $X_o(t) = \text{Tr}(\rho_o \hat{H}_{\text{eff}})$, entropy computation, normalization, and deterministic serialization; the final cryptographic hash over the serialized string is linear in input length.[file:202] Accordingly, stronger cryptographic primitives may increase the final encoding cost only modestly relative to the observable-construction stage for many realistic scientific workflows.[file:202]

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7. Practical Implementation

7.1 Time-Indexed Hashing

The framework supports deterministic time-indexed labeling through sequences of the form

$$\{(T_n, h_q^{(n)})\}_{n \in \mathbb{Z}},$$

allowing reproducible tracking of system states over time.[file:202] This construction is meaningful only when $\Delta t > 0$ and when the serialization policy for all time-dependent inputs remains fixed across evaluations.[file:202]

7.2 AI-Assisted Provenance

The resulting hash can serve as a stable linkage across datasets, simulations, outputs, and workflow states, enabling reconstruction of system configurations at the informational level rather than from raw state storage alone.[file:202] In this role, the framework acts as a provenance descriptor rather than as a compression of the underlying physical state.[file:202]

8. Biological Extension

For biological systems, a specialized deterministic descriptor is defined by

$$H_q^{\text{bio}} = \mathcal{H}(E_{\text{bio}}, S_{\text{bio}}, T, \text{bio-parameters}, \mathcal{C}_{\text{bio}}),$$

where E_{bio} is an effective biological energy or scale descriptor, S_{bio} is an entropy-based informational descriptor, T is the deterministic temporal index, and the bio-parameters encode structured metadata such as tissue type, experimental condition, or protocol identifiers.[file:202] To preserve internal coherence with the physical framework, the biological normalized entropy should also satisfy

$$0 \leq S_{\text{norm}}^{\text{bio}} \leq 1,$$

and the associated continuous descriptor should use the same bounded-normalization logic as in the non-biological case.[file:202]

The biological representation is not intended to encode raw sensitive biological data directly, but to provide a deterministic identifier for aggregated biological states and experimental

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configurations.[file:202] This preserves reproducibility while maintaining separation between underlying biological measurements and their informational indexing layer.[file:202]

9. Use Cases

Representative use cases include macroscopic systems, reference scaling tables, simulation identifiers, time-indexed configurations, dataset integrity verification, metadata linking, provenance tracking, anomaly detection, state clustering, biological sample tracking, cross-pipeline validation, and large-scale synthetic simulation environments.[file:202] In all these cases, the mathematical role of the framework is the same: deterministic indexing of structured state summaries rather than discovery of new observables.[file:202]

10. Discussion

The framework preserves deterministic structure, separates physical observables from informational representation, and supports multi-scale applicability through a consistent continuous-to-discrete mapping.[file:202] Its main mathematical strengths are explicit decomposition, bounded entropy normalization, a clearly delimited continuous descriptor, and reproducible final hashing once serialization is fixed.[file:202]

Its principal limitations are equally clear.[file:202] The framework is not itself a physical observable, it depends on class-specific parameter choices such as $S_{\max}$, S_{ref} , κ , and γ , and it requires operational standardization of metadata, units, causal coding, and serialization rules before interoperability can be guaranteed.[file:202]

11. Conclusion

A deterministic quantum hash framework is defined as a hybrid physical-informational descriptor for reproducible identification of system states across scales and domains.[file:202] The model is mathematically coherent when the density operator is restricted to valid quantum states, the energy scale is strictly positive for logarithmic representation, the entropy is normalized against an explicit bounded reference, the causal descriptor is encoded in a deterministic finite form, and the hash input is canonically serialized.[file:202] Under these conditions, the framework provides a stable and interpretable informational layer for provenance, indexing, and state tracking in physical, computational, and biological workflows.[file:202]

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